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The birds of Kesterson Reservoir: a historical perspective

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Abstract

Beginning in the late 1970s, Kesterson Reservoir was used for disposal of subsurface drainage from agricultural fields in California's San Joaquin Valley. During 1983–1985, studies were conducted to evaluate the effects of chemicals in this agricultural drainwater on aquatic birds using Kesterson Reservoir. These studies included analyses of food-chain biota (such as plants, aquatic invertebrates, and fish) and bird tissues or eggs, as well as measuring adverse effects on health and reproduction of the birds. Results of the integrated set of field and experimental studies showed that selenium was the only chemical found at concentrations high enough to cause the adverse effects on bird health or reproduction that were observed. This article provides a summary of the field studies conducted at Kesterson Reservoir (and some of the related field and experimental studies conducted elsewhere) to evaluate the effects of irrigation drainage water contaminants on aquatic birds.

Keywords: Kesterson Reservoir; Selenium; Agriculture; Birds

1. Introduction

During 1983–1985, we conducted studies of the effects of agricultural drainwater on birds at Kesterson Reservoir, which is located in California's San Joaquin Valley. The Reservoir consisted of a series of 12 ponds within the Kesterson National Wildlife Refuge (NWR) that were used for disposal of subsurface drainage from agricultural fields. The studies initially considered a broad array of inorganic and organic chemicals that were known or suspected to occur in the wastewater that originated from subsurface drainage systems in agricultural fields. However, analyses of food-chain biota (such as plants, aquatic invertebrates, and fish) as well as bird tissues or eggs showed that selenium was the only chemical found at concentrations high enough to cause the adverse effects on bird health or reproduction that were observed.

This article provides a summary of the field studies conducted at Kesterson Reservoir (and some of the related field and experimental studies conducted elsewhere) to evaluate the effects of irrigation drainage water contaminants on aquatic birds. The findings of these studies have been reported in a series of publications (e.g. Ohlendorf et al., 1986a,b, 1988, 1989, 1990; Hothem and Ohlendorf, 1989; Ohlendorf and Skorupa, 1989; Williams et al., 1989) and in several reviews that also incorporated the results of studies in other

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areas and those of related experimental studies (e.g. Ohlendorf, 1989, 1996; Skorupa and Ohlendorf, 1991; Ohlendorf et al., 1993; Oldfield et al., 1994; Ohlendorf and Hothem, 1995; Heinz, 1996).

Most of the related experimental studies were conducted with waterfowl (mallards, *Anas platyrhynchos*) at the Patuxent Wildlife Research Center in Maryland as a result of the findings at Kesterson Reservoir. However, some of the studies also were conducted with birds of other species (such as night-herons and owls). The studies were designed to determine whether the effects observed in the field were related to the levels of selenium in the birds' diets (as measured by analysis of typical food items eaten by the birds at Kesterson Reservoir), and to evaluate possible interactions of selenium with other contaminants (arsenic, boron, and mercury) that were found in drainwater at Kesterson or other sites. Although the experimental studies are described only briefly and in a separate section below, they were closely integrated with the field studies, and they provided strong support for the field-based observations.

One of the real strengths of the Kesterson-related studies is the integrated combination of field and laboratory studies that fulfilled the equivalent of Koch's postulates by recognizing a disease syndrome, identifying the causative agent, and reproducing the disease syndrome in healthy individuals by administration of the putative agent (selenium) in their diet. These studies have been recognized as one of the 'gold standards' of retrospective ecological risk assessment, as discussed by Suter (1993).

All selenium concentrations for biota in this paper are given on dry-weight basis.

1.1. Background

The following paragraphs, taken from the study plan for the initial study of birds using Kesterson Reservoir in 1983 (Ohlendorf, 1983), provide part of the justification for the study and the context within which the study was initiated.

Waterfowl and other birds that depend on wetland and riparian habitats in California's Central Valley faced an uncertain future; much of this habitat was altered by flood control, drainage, or water diversion projects, and by agricultural development (Gilmer et al., 1982; USFWS, 1982). All of the major wetlands in the Central Valley had inadequate water supplies, and the problem was expected to worsen as more water was needed for agriculture.

A review of published and unpublished literature had suggested that it might be feasible to create new or restore former wetland habitats by using irrigation drainage water for water management (Jones and Stokes, 1977). However, using low-quality water could adversely affect fish and wildlife resources, and many aspects of using irrigation drainage water for marsh management had not been adequately evaluated. Potential deleterious effects include direct and indirect effects on fish and wildlife populations by environmental contaminants, increased potential for disease outbreaks, and establishment of wetlands unsuitable for waterfowl and other wetland species.

Natural drainage is inadequate to maintain permanent productivity on certain valuable irrigated lands in the San Joaquin Valley (IDP, 1979; Hanson, 1982). These lands, located in the western portion of the Valley, require the installation of subsurface drains to collect shallow-lying saline groundwater and carry it away from the fields. Lack of disposal for the drainwater limited installation of the required subsurface drains. The US Bureau of Reclamation (USBR) obtained authority to construct the San Luis Drain, which was intended to carry the drainwater to the San Francisco Bay estuary for discharge. About 40% of the Drain was completed before construction was discontinued in 1975. The terminus of the Drain was at Kesterson Reservoir, where the water was impounded in 12 shallow ponds for evaporation and was intended to provide beneficial habitat for wildlife.

The California State Water Resources Control Board required that USBR complete a number of studies prior to approval of agricultural drainwater discharge to the Estuary. Due to concerns about the potential effects on fish and wildlife of chemicals in the drainwater, the USFWS proposed to USBR that studies be conducted at Kesterson, at the proposed discharge site, and at a reference site near Kesterson Reservoir that did not receive subsurface agricultural drainwater (Volta Wildlife Area). There was no requirement from the State Board for studies of wildlife using Kesterson Reservoir or the planned discharge site in the Estuary, so USBR declined to fund the proposed studies. Therefore, USFWS undertook the studies with its own funding.

Preliminary analyses of San Luis Drain water between March 1981 and February 1982 by the USBR (N. Cederquist, USBR, personal communication) identified several inorganic elements that approached or exceeded harmful concentrations for freshwater life (based on USEPA, 1976). These included arsenic (255–288 μg/l), cadmium (10–154 μg/l), chromium (30–60 μg/l), copper (20–40 μg/l), lead (10–150 μg/l), mercury (1 μg/l), nickel (40–140 μg/l), selenium (106–451 μg/l), silver (10–30 μg/l), and zinc (10–150 μg/l), among others. The tendency of some of these elements to bioaccumulate was of particular concern. Concentrations of organochlorines and various herbicides in the drainage effluent were unknown.

During 1971–1977, inflow to Kesterson Reservoir through the San Luis Drain was a mixture of fresh water and surface runoff from agricultural fields that provided high-quality wetland habitat for waterfowl and other wildlife. Increasing proportions of the flow were from subsurface drains during 1978–1980. Before 1980, the Drain supported fish of several species, including striped bass (*Morone saxatilis*), largemouth bass (*Micropterus salmoides*), green sunfish (*Lepomis cyanellus*), and channel catfish (*Ictalurus punctatus*). By 1982, only mosquitofish (*Gambusia affinis*) were common in the Drain and in Kesterson Reservoir. The high abundance of mosquitofish suggested that few predatory fish survived there.

Concentrations of selenium in a small sample of mosquitofish from the San Luis Drain (27–30 μg/g, wet weight) and from Kesterson Reservoir (26–31 μg/g) were much higher than in mosquitofish from a nearby reference area (Volta Wildlife Area, 0.39 μg/g) that did not receive subsurface drainage effluent (results subsequently published by Saiki, 1986). This suggested that mosquitofish are very tolerant of selenium and can accumulate high levels. Concentrations of several metals (As, Cd, Cr, Cu, Hg, Ni, Pb, and Zn) were generally similar in these preliminary samples, and concentrations of organochlorines were very low. Only two of 23 organochlorine compounds in the analytical suite were detected in the mosquitofish; these were *p,p′*-DDE (22–44 μg/kg) and Aroclor 1248 (60 μg/kg) in Drain or Kesterson fish. Concentrations of selenium and metals in aquatic plants and invertebrates at Kesterson were unknown.

A review of the literature indicated that avian embryos are very sensitive to selenium toxicity (Moxon and Olson, 1974; NAS, 1976; Ort and Latshaw, 1977, 1978). Hatchability of poultry eggs was significantly reduced by 5 μg/g of dietary selenium. At dietary concentrations between 5 and 10 μg/g, egg production was reduced and there was a high incidence of grossly deformed embryos. Those embryos were characterized by missing eyes and beaks, edema of the head and neck, and distorted wings and feet. Thus, selenium in the diet at about one-tenth the concentration found in mosquitofish (converted to dry-weight basis to be consistent with the poultry diet) from Kesterson Reservoir produced significant reproductive effects in chickens. The relative sensitivity of aquatic birds such as those inhabiting the Kesterson ponds was unknown.

This background information provided the impetus for a study to determine whether Kesterson Reservoir provided favorable habitat for aquatic wildlife, especially because of the potential for drainwater to be used elsewhere for marsh management or to be discharged into the San Francisco Bay Estuary.

2. The 1983 study

The objectives of the study in 1983 were to “determine whether selenium or heavy metals occur at harmful levels in aquatic birds or their food chains in the evaporation ponds at Kesterson NWR and interpret the significance of these contaminants to wildlife” (Ohlendorf, 1983).

2.1. Methods and study areas

The study focused on aquatic birds and their food chains at Kesterson Reservoir and Volta Wildlife Area (the nearby reference site that did not receive subsurface drainage water). Sample collections included several species of birds that were common at one or both of the study sites. These species included eared grebe (*Podiceps nigricollis*), pied-billed grebe (*Podilymbus podiceps*), American coot (*Fulica americana*), mallard, gadwall (*A. strepera*), cinnamon teal (*A. cyanoptera*), American avocet (*Recurvirostra americana*), black-necked stilt (*Himantopus mexicanus*), and killdeer (*Charadrius vociferus*). Adult birds of four species per site were collected in spring and early summer to determine which foods they were eating from the Kesterson ponds, and what concentrations of selenium were in their tissues. Pre-fledging juvenile birds of some of these species also were sampled to determine concentrations of chemicals in their tissues, because their exposure (as non-flying young) could be more definitively associated with the area in which they were collected.

Nesting success of these species was studied by searching for nests in favorable nesting habitats at Kesterson and Volta, marking the nests, and monitoring them to determine their fate. Randomly selected eggs were collected from a subset of the nests and non-random eggs (those that failed to hatch or sibling eggs from nests where abnormal chicks were found) were collected for analysis.

Aquatic invertebrates and plants of the types eaten by the aquatic birds were sampled in a parallel study (Saiki and Lowe, 1987). The food-chain sampling included seasonal and spatial comparisons to evaluate changes related to inflows of agricultural drainwater and its evaporation during the summer.

A major effort of the aquatic bird study involved searching for, marking, and monitoring the nests of the study species. This focus was warranted because impaired reproduction was likely to be a significant effect of the birds' exposure to selenium.

2.2. Results and discussion

Eared grebes, American coots, various duck species, stilts, and avocets nested at Kesterson in large enough numbers so it was possible to follow a total of 347 nests to late stages of incubation or hatching and evaluate reproductive success (Ohlendorf et al., 1986a). Of those nests, 40% had one or more dead embryos and 20% had one or more embryos or chicks with severe developmental abnormalities. When compared with the Volta reference area and findings elsewhere in studies with these species, the incidences of embryo mortality or abnormality were far higher than expected. The developmental abnormalities were similar to those previously found in poultry and mallards, and were severe enough to be fatal. The abnormalities were often multiple and included missing or abnormal eyes (anophthalmia and microphthalmia), beaks (missing, reduced, or crossed), legs and wings (micromelia and amelia), feet (ectrodactyly and clubfoot), and brain (hydrocephaly and exencephaly).

Livers of adult and juvenile birds from Kesterson contained selenium concentrations that were about ten times those found at the Volta reference site (Ohlendorf et al., 1986a, 1990). Similarly, mean selenium concentrations in bird eggs at Kesterson were usually 20–30 times higher than at Volta (Ohlendorf and Hothem, 1995). All species means at Volta were less than 3 μg/g (dry weight) and typical of normal background, whereas means at Kesterson ranged up to 69.7 μg/g (the mean for eared grebes).

Selenium concentrations in food-chain organisms such as those eaten by the aquatic birds we studied also were highly elevated (Ohlendorf et al. 1986a; Saiki, 1986; Saiki and Lowe, 1987). Selenium concentrations in algae, rooted plants, net plankton, aquatic insects of various kinds, and mosquitofish from the Kesterson ponds and the San Luis Drain averaged 20–332 μg/g (dry weight), and often were 100 times those found at Volta. These dietary selenium concentrations were well above the range of concentrations (5–10 μg/g) that had caused severe reproductive impairment in earlier studies with poultry (summarized by Moxon and Olson, 1974; NAS, 1976).

Selenium concentrations in the inflow to Kesterson averaged 300 μg/l, in comparison to less than 2 μg/l for the Volta ponds (Saiki and Lowe, 1987). Selenium concentrations in biota were highest in samples from the San Luis Drain and from the first ponds where the drainwater entered Kesterson. Thus, the elevated levels in biota were not the result of evaporative concentration of selenium in the drainwater within Kesterson, which has sometimes been a misconception about the behavior of selenium in wetlands such as the Kesterson ponds.

The preliminary results of this first study at Kesterson were reported in the news media, beginning with a first article in the Fresno Bee on 21 September 1983 (Blum, 1983). This article was followed by a large number of other articles (which were not always accurate) as well as reports in other news media throughout the next several years. The research findings received a large amount of public attention for several reasons. The Reservoir was part of the Kesterson NWR, and it was shocking to many people to learn of the nature and magnitude of effects that were observed. Instead of providing favorable wetland habitat for wildlife at the Refuge as intended, the water was found to be contaminated, and it caused dramatic negative effects on the wildlife it was supposed to benefit. Photographs showing deformities of the bird embryos made it clear that something was wrong at the site. In the age of mass media, these images were shown on television and in newspapers to audiences in the region and then throughout the various communication networks. Opponents of completion of the San Luis Drain to discharge agricultural drainage to the San Francisco estuary seized upon the findings of the Kesterson studies to fight that controversial project. In addition, there were substantial disagreements among involved federal agencies as to the significance of the findings (see review by Garone, 1999).

The results from the 1983 field study helped define the needs for a series of laboratory and field studies to further define the nature and extent of contaminant issues related to agricultural drainage water. These studies in 1984 included further research at Kesterson, a field study in the surrounding Grassland Water District (Ohlendorf et al., 1987), and the first in a series of experimental feeding studies under controlled conditions at the Patuxent Wildlife Research Center (summarized by Heinz, 1996).

3. 1984–1985 Kesterson studies

In 1984 and 1985, we continued to measure selenium bioaccumulation in food chain organisms at Kesterson and Volta, and to evaluate the effects of selenium on aquatic birds at the two sites. Findings for food-chain organisms (Hothem and Ohlendorf, 1989; Schuler et al., 1990) were similar to those in 1983. Selenium concentrations in aquatic plants, invertebrates (mostly insects), and mosquitofish at Kesterson typically averaged 50–150 μg/g, and were far higher than the threshold dietary levels associated with impaired reproduction for poultry (Moxon and Olson, 1974; NAS, 1976) or mallards (as determined by studies conducted at the Patuxent Wildlife Research Center; see Heinz, 1996). In contrast, food-chain organisms from Volta usually averaged 2 μg/g or less, which is typical of uncontaminated areas. Bioaccumulation factors (tissue concentration divided by waterborne selenium concentration) were generally about 1000, so concentrations for many organisms (μg/g dry weight) could be estimated by multiplying waterborne concentrations (μg/l) by 1000.

Although coots were present at Kesterson in large numbers during the 1984 and 1985 nesting seasons, no nests were found in areas where 92 coot nests had been found in 1983. Instead, we found many dead coots (as well as some ducks, grebes, and other birds) at Kesterson. This mortality and failure to nest were attributed to the debilitating effects of excess selenium in the birds' diets and tissues (Ohlendorf et al., 1988, 1990; Ohlendorf, 1989, 1996). Live as well as dead coots at Kesterson were about 25% below their normal body weights, their livers contained higher concentrations of selenium than in 1983, and they had lesions associated with selenium toxicosis.

Impaired reproduction due to embryo abnormalities and mortality, as well as poor survival of chicks that hatched, was documented for several species of aquatic birds in 1984 and 1985 (Ohlendorf, 1989; Ohlendorf et al., 1989; Williams et al., 1989). Overall, at least 39% of the 578 nests that could be evaluated during 1983–1985 contained at least one dead or deformed embryo or chick. Some embryo mortality is expected to occur normally, but only about 1% of the eggs from Volta contained dead embryos, and no abnormal embryos were found there. Among the young that were presumed to have hatched at Kesterson, there was poor survival in grebes and coots (about 2%) in 1983. In 1984–1985, observations indicated there was no survival among the nearly 440 avocets and stilts that apparently hatched.

4. Related field studies

In 1984, we also sampled birds and their eggs from the Grassland Water District, which is located near Kesterson and farther south (nearer the source areas of the agricultural drainage water; see Ohlendorf et al., 1987). The Grasslands received a mixture of subsurface agricultural drainage and other water, with an average selenium concentration in the inflow of about 50 μg/l. Elevated selenium levels were found in several species of aquatic birds and their eggs. The spatial pattern of selenium concentrations within the Grasslands was similar to that at Kesterson; selenium concentrations were higher in the South Grasslands, near the inflow areas, than farther downstream in the North Grasslands. As a result of this study, a freshwater supply to the Grasslands was substituted for irrigation drainage water during the autumn of 1985.

This study was followed by a 2-year study of reproductive success of ducks and shorebirds nesting in the Grasslands during 1986 and 1987 (Hothem and Welsh, 1994). Concentrations of arsenic and boron in eggs were below those known to cause adverse reproductive effects in mallards. In contrast, concentrations of selenium were higher in eggs from the Grasslands than at an uncontaminated reference site, and they exceeded known effect levels in some species and locations. Nevertheless, reproductive impairment was not observed in any ducks or shorebirds nesting in the Grasslands in 1986 or 1987, probably because of the small sample size for the more contaminated areas.

Sampling of birds throughout the Grasslands for tissue analysis also was conducted in 1985–1988 (Paveglio et al., 1992) and in 1989 and 1994 (Paveglio et al., 1997) to further define the spatial and species patterns of contamination and to determine improvements resulting from the change to freshwater supply for the Grasslands. These studies showed that the South Grasslands continued to be more contaminated than the North Grasslands, and that livers of birds during the breeding and wintering periods contained selenium at levels associated with reproductive impairment. Although selenium contamination (as reflected by bird livers) had been reduced as a result of the change in water source for the Grasslands, concentrations still were higher than background, and sometimes exceeded levels associated with adverse effects.

Following the discoveries of irrigation drainage-related contamination issues at Kesterson Reservoir, the US Department of the Interior (DOI) implemented the National Irrigation Water Quality Program (NIWQP) in 1985 to study the effects of irrigation drainage on water resources and on fish and wildlife (Deason, 1986; Seiler et al., 1999). The NIWQP screened existing data from DOI facilities, including irrigation or irrigation–drainage facilities and national wildlife refuges, in the conterminous western US to identify other areas in which agricultural drainage might present contamination problems. As a result, 26 areas were identified for investigation. Since initial reconnaissance-level sampling at nine of those areas confirmed that harmful effects either had occurred or were likely to occur, more detailed studies were conducted at those nine areas. Bird embryos with multiple overt deformities, like those in birds from Kesterson Reservoir, were found in four of the 26 NIWQP areas (in California, Colorado, Utah, and Wyoming; see Seiler et al., 1999 for summary). Waterborne selenium concentrations in those areas were greatly elevated, but they were lower than the average inflow concentrations to Kesterson Reservoir (about 300 μg/l; Ohlendorf, 1989).

These investigations led to the publication of a series of US Geological Survey reports for the individual study areas, and to several reports that analyzed and synthesized the results for the NIWQP. The individual reports are listed in the synthesis reports, such as the one by Seiler et al. (1999) that identified areas that are susceptible to irrigation-induced selenium contamination of water and biota.

5. Kesterson Reservoir since 1985

USBR undertook several studies and control actions to reduce the hazard of selenium exposure to aquatic birds (USBR, 1986; USDI, 1989). In particular, USBR halted inflows of agricultural drainage to Kesterson in 1986 and subsequently, in 1988, de-watered the reservoir and filled all areas to at least 15 cm above the expected seasonal (winter) elevation of high-selenium groundwater. These actions effectively transformed the Reservoir into terrestrial habitats, as described by Ohlendorf and Santolo (1994).

Monitoring has been conducted since 1987 to measure selenium concentrations in representative plants and animals using the site and to determine whether adverse effects occurred (Ohlendorf and Santolo, 1994). The data from the monitoring program during 1989–1991 were used to estimate likely future levels of selenium in various biota, assess risks of adverse effects to animals using the site, identify needs for contingency plans for site management, and recommend further research and monitoring to provide the information needed to improve management of the site.

The risk assessment concluded that selenium concentrations in terrestrial plants and animals were not expected to change markedly in the next 20 years (Ohlendorf and Santolo, 1994). No adverse effects had been documented in terrestrial birds or mammals, and no adverse effects were expected in the future.

Surface ponding of rainwater occurs in some portions of Kesterson Reservoir during very wet winters (Ohlendorf and Santolo, 1994). Ephemeral pools that form under current conditions, and those expected to occur in the future, result from the accumulation of rainwater, rather than from rising groundwater. Although these pools are formed by rainwater, selenium concentrations in the pools averaged less than 10 μg/l, but concentrations up to 162 μg/l were measured in some pools. These concentrations and those in aquatic invertebrates collected from them were high enough to be of concern for aquatic birds (such as waterfowl and shorebirds). The greatest concern was that these pools may form during late winter or spring and persist during the nesting season of aquatic birds, which might feed on aquatic plants and invertebrates in the pools if they persisted long enough to support these food-chain components.

As a result of the ecological risk assessment, the monitoring program was revised in 1995 to be less costly (e.g. sampling fewer kinds of biota, and sampling less frequently) but still sufficient to determine whether the model predictions (described above) were correct, and further studies (e.g. Yamamoto et al., 1998; Santolo et al., 1999) were conducted during subsequent years to resolve some of the unknowns identified by the risk assessment.

This new information, along with monitoring results since 1989, was evaluated in a subsequent ecological risk assessment that focused on the terrestrial and aquatic wildlife using the site (CH2M HILL and LBNL, 2000). The overall conclusions of the risk assessment were that future soluble (i.e. bioavailable) soil selenium levels will be similar to those observed over the past decade, waterborne selenium concentrations in rainwater pools can be predicted on the basis of soil selenium where the pools form, and selenium concentrations in terrestrial and rainwater-pool biota will continue to be elevated above normal background-site levels, but there is low risk to wildlife for several reasons. A model developed using the historic (127-year) Kesterson-area rainfall data and observed ponding on the site since 1989 (including winter of 1997–1998, the year of maximum rainfall) indicated that there is low probability that substantial portions of the site would be flooded during the spring breeding season for birds, so their exposure during that critical period would be minimal. Selenium concentrations in terrestrial birds and mammals also will be greater than normal background, but they are expected to be below levels known to cause health or reproductive effects.

Following the closure of Kesterson Reservoir as a disposal site for subsurface agricultural drainage, growers were required to find on-farm ways of managing salinity-affected lands and any associated subsurface drainage water that was collected from the lands. Examples include increasing the efficiency of irrigation (thereby generating less drainage water for disposal), re-cycling/blending the drainage water with fresh water and using it for irrigation, and growing more salt-tolerant crops.

6. Experimental studies

Since 1984, a series of experimental studies has been conducted to determine the effects of selenium (as well as a few other drainwater contaminants) on birds other than domestic poultry. Most of these studies were conducted with mallards by the Patuxent Wildlife Research Center, located near Laurel, Maryland, but studies also have been conducted elsewhere and with other species (e.g. O'Toole and Raisbeck, 1997; Yamamoto et al., 1998; Santolo et al., 1999). These studies have confirmed that the health and reproductive effects observed in the field could be attributed to the toxicity of selenium, as exhibited by mortality and abnormal development of the avian embryos and by the weight loss and mortality of adults. They clearly show that a combination of observed effects (e.g. characteristic multiple deformities of embryos/hatchlings, pathological tissue changes of the integument [including feather loss] and liver, and death) and tissue analyses (especially of diets, eggs, and livers) can be used to diagnose selenium toxicosis in birds. Results of many of those studies published through 1995 were described in other reviews (e.g. Heinz, 1996; Ohlendorf, 1996; O'Toole and Raisbeck, 1998), and are not reiterated here.

Recent studies also have evaluated the interactive effects of selenium with arsenic, boron, or mercury in mallards (Stanley et al., 1994, 1996; Heinz and Hoffman, 1998). Antagonistic interactions between arsenic and selenium occurred whereby arsenic reduced selenium accumulation in livers and eggs of the ducks, and it alleviated the effects of selenium on hatching success and embryo deformities. In contrast, there was little evidence of interactive effects of boron and selenium, although each chemical caused effects when fed separately to the ducks. Exposure of adult mallards to mercury and selenium individually resulted in toxicity and mortality, but exposure-equivalent doses to both elements in combination were antagonistic, resulting in no adverse effects. However, these chemicals interacted synergistically in young birds, in that teratogenic effects were greater for the combination of these elements than they were for each one individually.

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References

Blum, D., 1983. Mineral is linked to bird deformities. The Fresno Bee, A1, A14.

CH2M HILL and Lawrence Berkeley National Laboratory (CH2M HILL and LBNL), 2000. Ecological Risk Assessment for Kesterson Reservoir, Prepared for US Bureau of Reclamation Mid-Pacific Region, Sacramento, CA, December.

Deason, J.P., 1986. US Department of the Interior investigations of irrigation-induced contamination problems. In: Summers, J.B., Anderson, S.S. (Eds.), Toxic Substances in Agricultural Water Supply and Drainage—Defining the Problem—Proceedings of Regional Meeting of the U.S. Committee on Irrigation and Drainage, September 1986, Boulder, CO. US Government Printing Office, Washington, DC, pp. 201–210.

Garone, P., 1999. The tragedy at Kesterson Reservoir: a case study in environmental history and a lesson in ecological complexity. Environs 22, 107–144.

Gilmer, D.S., Miller, M.R., Bauer, R.D., LeDonne, J.R., 1982. California's Central Valley wintering waterfowl: concerns and challenges. Trans. N. Am. Wildl. Nat. Resour. Conf. 47, 441–452.

Hanson, B.R., 1982. A master plan for drainage in the San Joaquin Valley. Calif. Agric. 36 (5/6), 9–11.

Heinz, G.H., 1996. Selenium in birds. In: Beyer, W.N., Heinz, G.H., Redmon-Norwood, A.W. (Eds.), Environmental Contaminants in Wildlife: Interpreting Tissue Concentrations. Lewis, Boca Raton, FL, pp. 447–458.

Hothem, R.L., Ohlendorf, H.M., 1989. Contaminants in foods of aquatic birds at Kesterson Reservoir, California. Arch. Environ. Contam. Toxicol. 18, 773–786.

Hothem, R.L., Ohlendorf, H.M., 1989. Contaminants in foods of aquatic birds at Kesterson Reservoir, California. Arch. Environ. Contam. Toxicol. 18, 773–786.

Hothem, R.L., Welsh, D., 1994. Contaminants in eggs of aquatic birds from the Grasslands of Central California. Arch. Environ. Contam. Toxicol. 27, 180–185.

Interagency Drainage Program (IDP), 1979. Agricultural drainage and salt management in the San Joaquin Valley. Final Report Including Recommended Plan and First-Stage Environmental Impact Report. San Joaquin Valley Interagency Drainage Program: US Bureau of Reclamation, California Department of Water Resources, and California State Water Resources Control Board. 189 pp. + appendices.

Jones and Stokes, 1977. An evaluation of the feasibility of utilizing agricultural tile drainage water for marsh management in the San Joaquin Valley, California. Prepared for US Fish and Wildlife Service and US Bureau of Reclamation by Jones and Stokes Associates, Inc. Sacramento, CA 172 pp.

Moxon, A.L., Olson, O.E., 1974. Selenium in agriculture. In: Zingaro, R.A., Cooper, W.C. (Eds.), Selenium. Van Nostrand Reinhold, New York, pp. 675–707.

National Academy of Sciences (NAS), 1976. Medical and biologic effects of environmental pollutants. In: Selenium. Division of Medical Sciences, National Research Council, NAS, Washington, DC, 203 pp.

O'Toole, D., Raisbeck, M.F., 1997. Experimentally induced selenosis of adult mallard ducks: clinical signs, lesions, and toxicology. Vet. Pathol. 34, 330–340.

O'Toole, D., Raisbeck, M.F., 1998. Magic numbers, elusive lesions: comparative pathology and toxicology of selenosis in waterfowl and mammalian species. In: Frankenberger, W.T. Jr, Engberg, R.A. (Eds.), Environmental Chemistry of Selenium. Marcel Dekker, New York, pp. 355–395.

Ohlendorf, H.M., 1983. Environmental contaminants in aquatic birds and their food chains in marsh habitats created by using San Luis Drain water. Study Plan 906.01.03. Patuxent Wildlife Research Center, US Fish and Wildlife Service, Laurel, Maryland. March 15.

Ohlendorf, H.M., 1989. Bioaccumulation and effects of selenium in wildlife. In: Jacobs, L.W. (Ed.), Selenium in Agriculture and the Environment. Soil Science Society of America, Madison, WI, pp. 133–177 Special Publication No. 23.

Ohlendorf, H.M., 1996. Selenium. In: Fairbrother, A., Hoff, G.L., Locke, L.N. (Eds.), Noninfectious Diseases of Wildlife, Second ed. Iowa State University Press, Ames, pp. 128–140.

Ohlendorf, H.M., Skorupa, J.P., 1989. Selenium in relation to wildlife and agricultural drainage water. In: Carapella, S.C. Jr (Ed.), Proceedings, Fourth International Symposium on Uses of Selenium and Tellurium, 8-10 May 1989, Banff, Alberta. Selenium-Tellurium Development Association, Inc, Darien, CT, pp. 314–338.

Ohlendorf, H.M., Santolo, G.M., 1994. Kesterson Reservoir—past present, and future: An ecological risk assessment. In: Frankenberger, W.T. Jr, Benson, S. (Eds.), Selenium in the Environment. Marcel Dekker, New York, pp. 69–117.

Ohlendorf, H.M., Hothem, R.L., 1995. Agricultural drainwater effects on wildlife in central California. In: Hoffman, D.J., Rattner, B.A., Burton, G.A. Jr, Cairns, J. (Eds.), Handbook of Ecotoxicology. Lewis Publishers, Boca Raton, FL, pp. 577–595.

Ohlendorf, H.M., Hoffman, D.J., Saiki, M.K., Aldrich, T.W., 1986a. Embryonic mortality and abnormalities of aquatic birds: apparent impacts of selenium from irrigation drainwater. Sci. Total Environ. 52, 49–63.

Ohlendorf, H.M., Hothem, R.L., Bunck, C.M., Aldrich, T.W., Moore, J.F., 1986b. Relationships between selenium concentrations and avian reproduction. Trans. N. Am. Wildl. Nat. Resour. Conf. 51, 330–342.

Ohlendorf, H.M., Hothem, R.L., Aldrich, T.W., Krynitsky, A.J., 1987. Selenium contamination of the grasslands, a major California waterfowl area. Sci. Total Environ. 66, 169–183.

Ohlendorf, H.M., Kilness, A.W., Simmons, J.L., Stroud, R.K., Hoffman, D.J., Moore, J.F., 1988. Selenium toxicosis in wild aquatic birds. J. Toxicol. Environ. Health 24, 67–92.

Ohlendorf, H.M., Hothem, R.L., Welsh, D., 1989. Nest success, cause-specific nest failure, and hatchability of aquatic birds at selenium-contaminated Kesterson Reservoir and a reference site. Condor 91, 787–796.

Ohlendorf, H.M., Hothem, R.L., Bunck, C.M., Marois, K.C., 1990. Bioaccumulation of selenium in birds at Kesterson Reservoir California. Arch. Environ. Contam. Toxicol. 19, 495–507.

Ohlendorf, H.M., Skorupa, J.P., Saiki, M.K., Barnum, D.A., 1993. Food-chain transfer of trace elements to wildlife. In:

Allen, R.G., Neale, C.M.U. (Eds.), Management of Irrigation and Drainage Systems: Integrated Perspectives. American Society of Civil Engineers, New York, pp. 596–603.

Oldfield, J.E., Bureau, R., Moller, G., Ohlendorf, H.M., Ullrey, D., 1994. Risks and benefits of selenium in agriculture. Issue Paper No. 3 and Supplement. Council for Agricultural Science and Technology, Ames, Iowa.

Ort, J.F., Latshaw, J.D., 1977. The effect of intermediate levels of selenium in the diets of S.C.W.L. laying hens. Poultry Sci. 56, 1744.

Ort, J.F., Latshaw, J.D., 1978. The toxic level of sodium selenite in the diet of laying chickens. J. Nutr. 108, 1114–1120.

Paveglio, F.L., Bunck, C.M., Heinz, G.H., 1992. Selenium and boron in aquatic birds from Central California. J. Wildl. Manage. 56, 31–42.

Paveglio, F.L., Kilbride, K.M., Bunck, C.M., 1997. Selenium in aquatic birds from Central California. J. Wildl. Manage. 61, 832–839.

Saiki, M.K., 1986. Concentrations of selenium in aquatic food-chain organisms and fish exposed to agricultural tile drainage water. In Howard, A.Q., (Ed.), Selenium and Agricultural Drainage: Implications for San Francisco Bay and the California Environment. Proceedings of the Second Selenium Symposium, 23 March 1985, Berkeley, California, pp. 25–33.

Saiki, M.K., Lowe, T.P., 1987. Selenium in aquatic organisms from subsurface agricultural drainage water, San Joaquin Valley, California. Arch. Environ. Contam. Toxicol. 16, 657–670.

Santolo, G.M., Yamamoto, J.T., Pisenti, J.M., Wilson, B.W., 1999. Selenium accumulation and effects on reproduction in captive American kestrels fed selenomethionine. J. Wildl. Manage. 63, 502–511.

Schuler, C.A., Anthony, R.G., Ohlendorf, H.M., 1990. Selenium in wetlands and waterfowl foods at Kesterson Reservoir, California, 1984. Arch. Environ. Contam. Toxicol. 19, 845–853.

Seiler, R.L., Skorupa, J.P., Peltz, L.A., 1999. Areas susceptible to irrigation-induced selenium contamination of water and biota in the western United States. US Geological Survey Circular 1180, Denver, Colorado.

Skorupa, J.P., Ohlendorf, H.M., 1991. Contaminants in drainage water and avian risk thresholds. In: Dinar, A., Zilberman, D. (Eds.), The Economics and Management of Water and Drainage in Agriculture. Kluwer Academic Publishers, Boston, pp. 345–368.

Stanley, T.R. Jr, Spann, J.W., Smith, G.J., Rosscoe, R., 1994. Main and interactive effects of arsenic and selenium on mallard reproduction and duckling growth and survival. Arch. Environ. Contam. Toxicol. 26, 444–451.

Stanley, T.R. Jr, Smith, G.J., Hoffman, D.J., Heinz, G.H., Rosscoe, R., 1996. Effects of boron and selenium on mallard reproduction and duckling growth and survival. Environ. Toxicol. Chem. 15, 1124–1132.

Suter, G.W. II, 1993. Ecological Risk Assessment. Lewis Publishers, Boca Raton, FL.

US Bureau of Reclamation (USBR), 1986. Final Environmental Impact Statement, Kesterson Reservoir. USBR, Mid-Pacific Region, in cooperation with USFWS and US Army Corps of Engineers.

US Department of the Interior (USDI), 1989. Submission to California State Water Resources Control Board in Response to Order No. WQ-88-7, Effectiveness of Filling Ephemeral Pools at Kesterson Reservoir, Kesterson Program Upland Habitat Assessment, and Kesterson Reservoir Final Cleanup Plan.

US Environmental Protection Agency (USEPA), 1976. Quality criteria for water. USEPA, Washington, DC. 256 pp.

US Fish and Wildlife Service (USFWS), 1982. Regional resource plan, Region 1. USFWS, Portland, Oregon.

Williams, M.L., Hothem, R.L., Ohlendorf, H.M., 1989. Recruitment failure in American avocets and black-necked stilts nesting at Kesterson Reservoir, California. Condor 91, 797–802.

Yamamoto, J.T., Santolo, G.M., Wilson, B.W., 1998. Selenium accumulation in captive American kestrels (*Falco sparverius*) fed selenomethionine and naturally incorporated selenium. Environ. Toxicol. Chem. 17, 2494–2497.